Radiation Environments for Lunar Programs

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Developing reliable space systems for lunar exploration and infrastructure for extended duration operations on the lunar surface requires analysis and mitigation of potential system vulnerabilities to radiation effects on materials and systems. This paper reviews the characteristics of space radiation environments relevant to lunar programs including the trans-Earth and trans-lunar injection trajectories through the Earth's radiation belts, solar wind surface dose environments, energetic solar particle events, and galactic cosmic rays and discusses the radiation design environments being developed for lunar program requirements to assure that systems operate successfully in the space environment.

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Space Technology Applications International Forum
Albuquerque, NM, 12-15 February 2007

Overview

- Radiation environments will be a prime concern for future long term lunar missions
- How different are lunar environments compared to the well characterized LEO, GEO environments?
- Constellation radiation design environments

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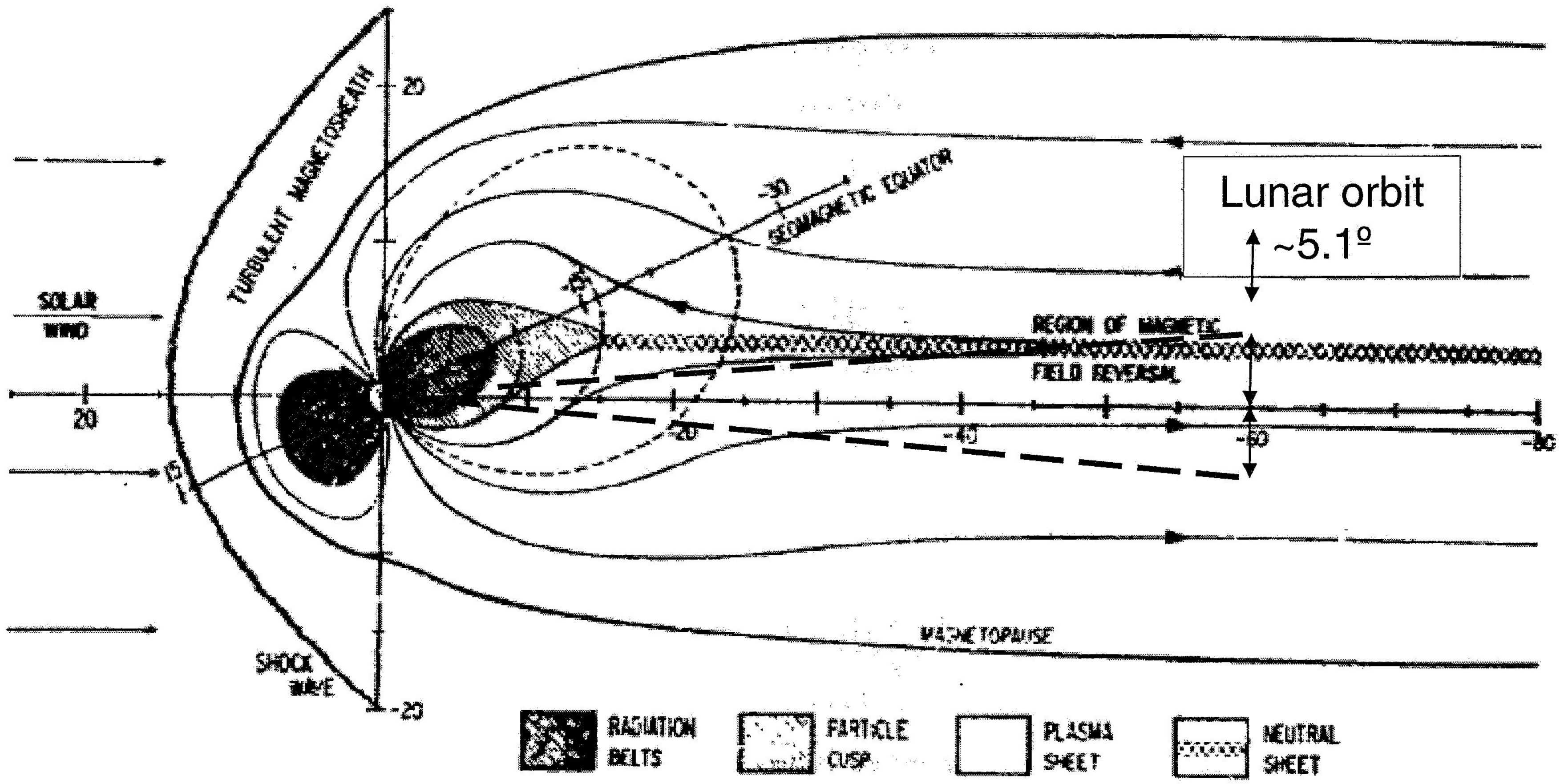
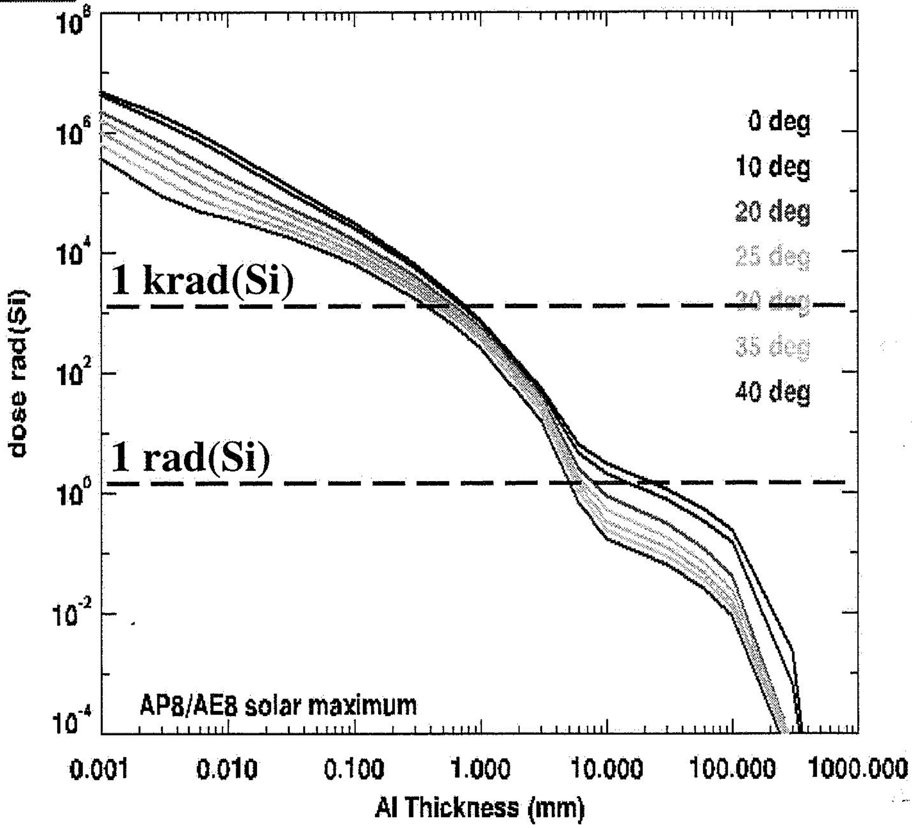
Environments	Space System Effects
Galactic cosmic rays	SEE, crew dose
Solar particle events	SEE, TID, crew dose
Trapped radiation	SEE, TID, charging
Solar wind, magnetosphere, plasma sheath	TID, charging
Lunar photoelectrons	dust charging

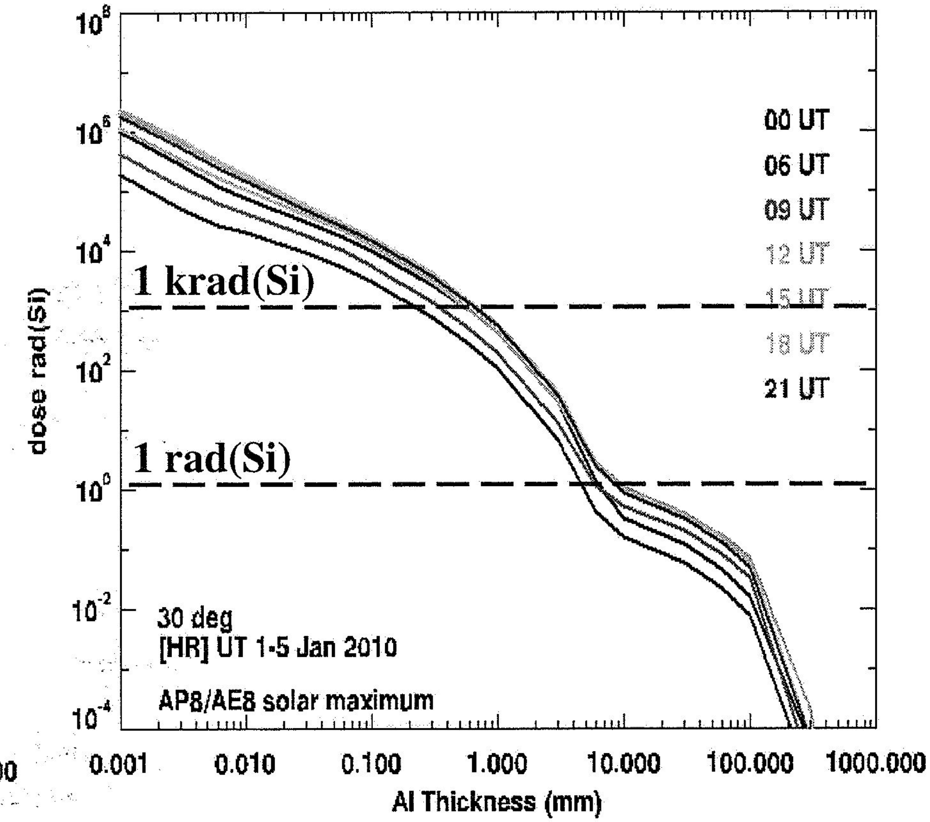
Magnetosphere and Lunar Orbit

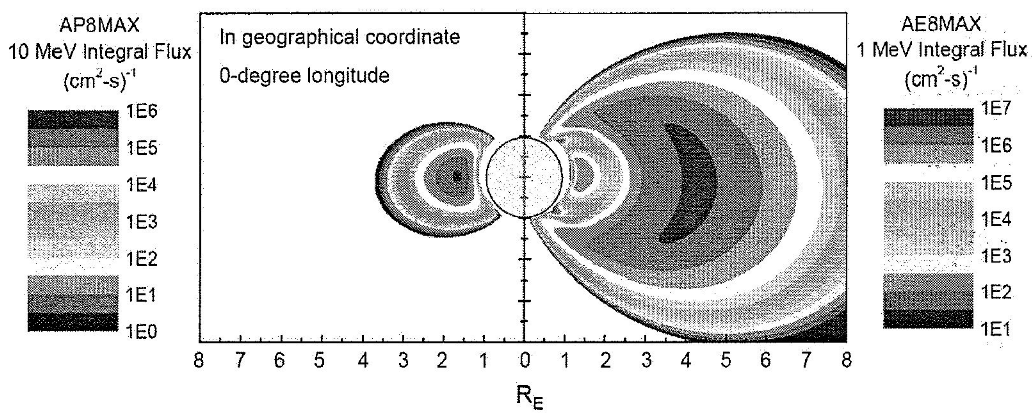


Adams et al., 1981

Inclination, Departure Longitude and Dose





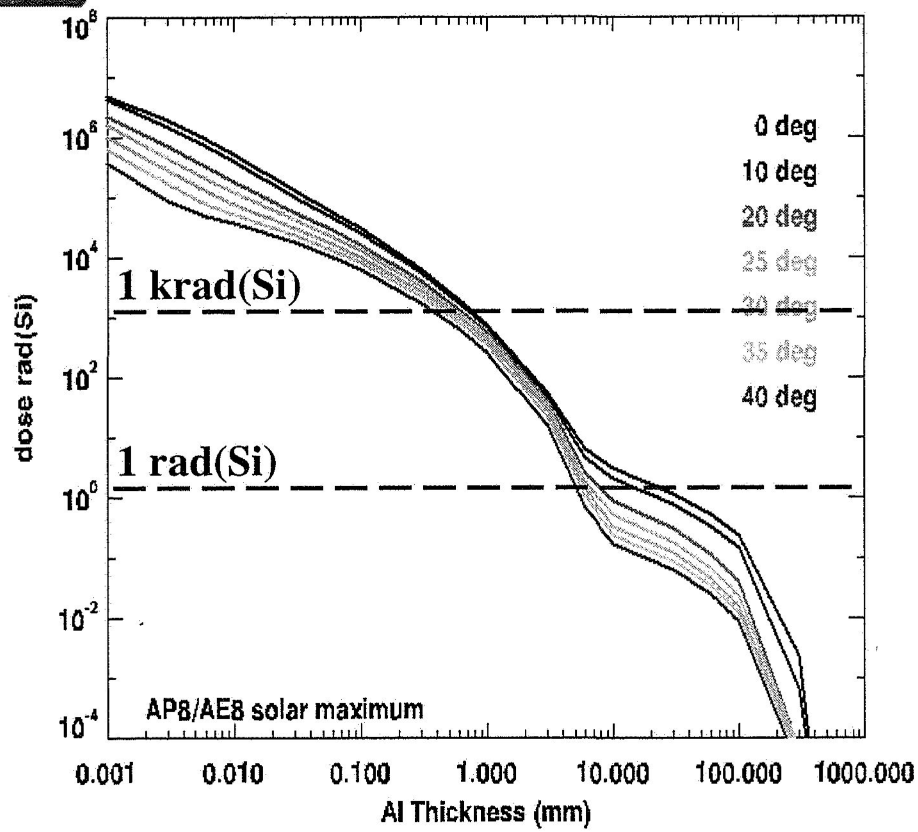


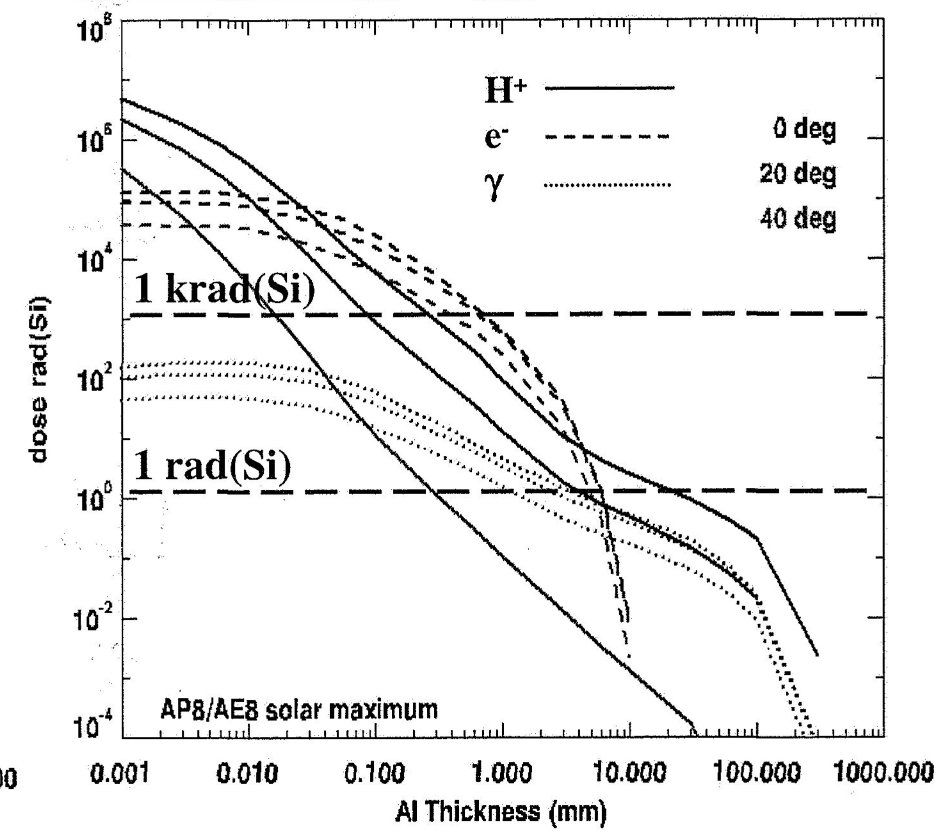
Single TLI orbit

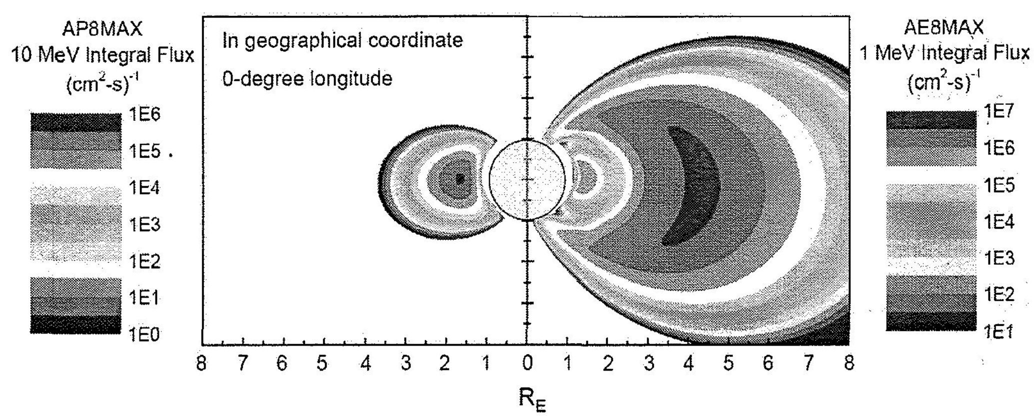
perigee = 300 km

apogee = 379,867 km

Inclination, Departure Longitude and Dose







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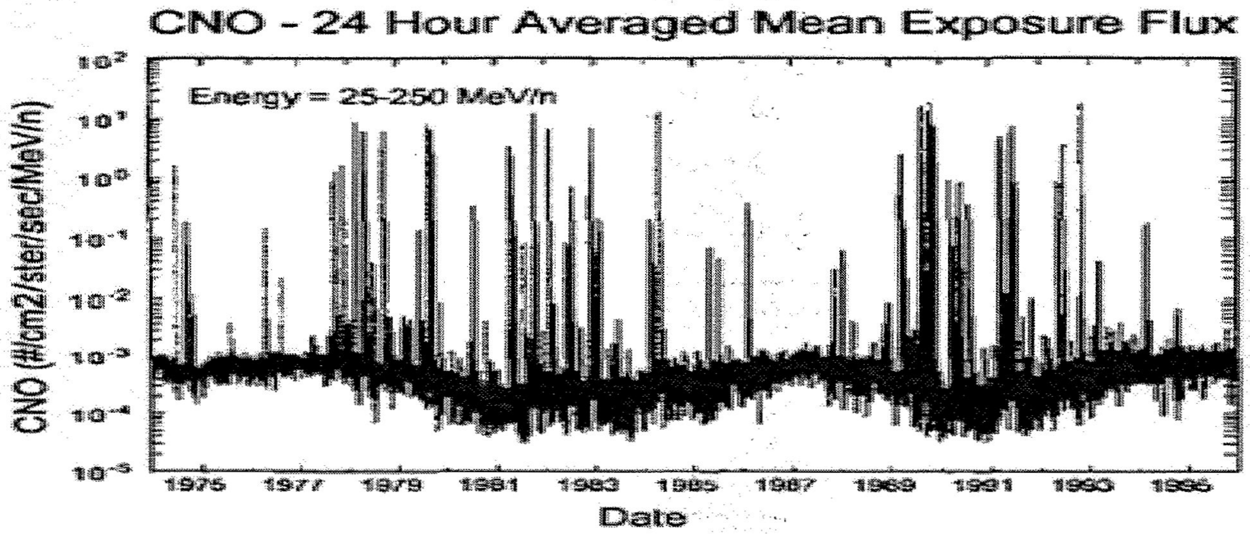
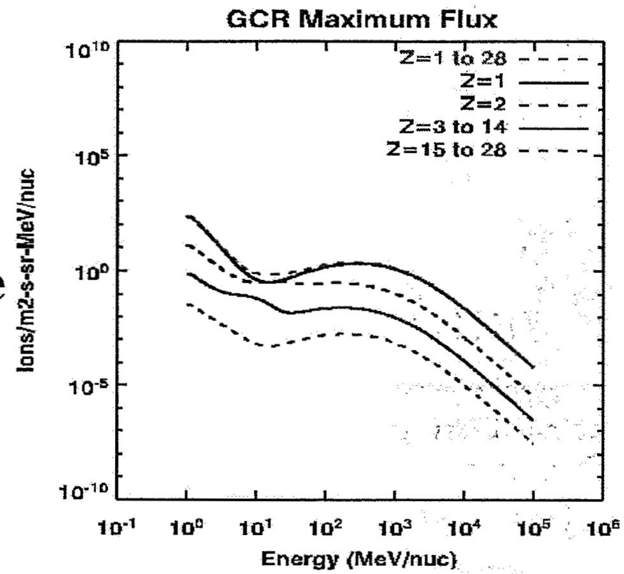
Galactic Cosmic Rays, Solar Energetic Particles

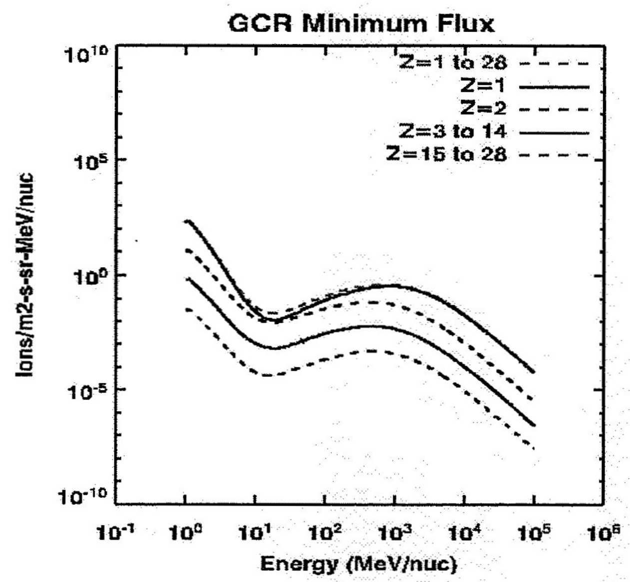


Lunar 60 Re orbit is ~1 ± 0.0026 AU

--Same cosmic ray, solar energetic particle environment as Earth

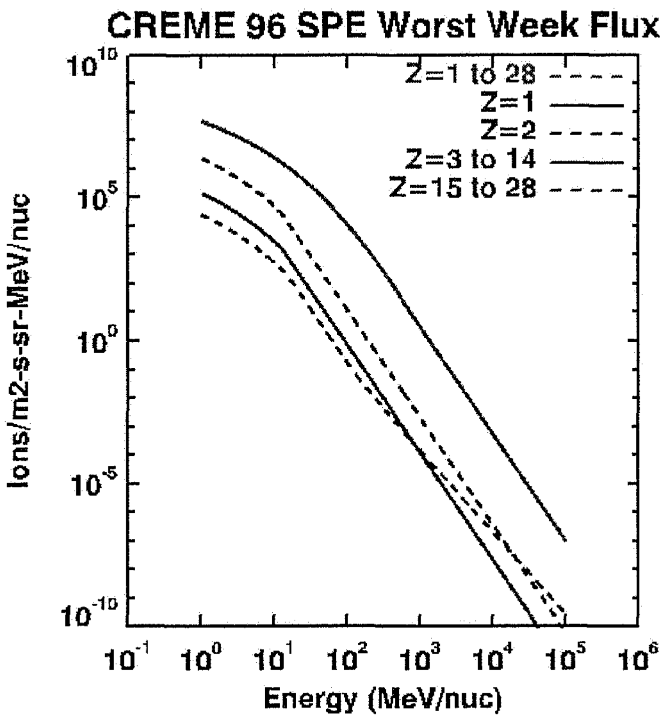
--Magnetotail ~10 nT field at lunar orbit weaker than the 50 nT to 100 nT at GEO

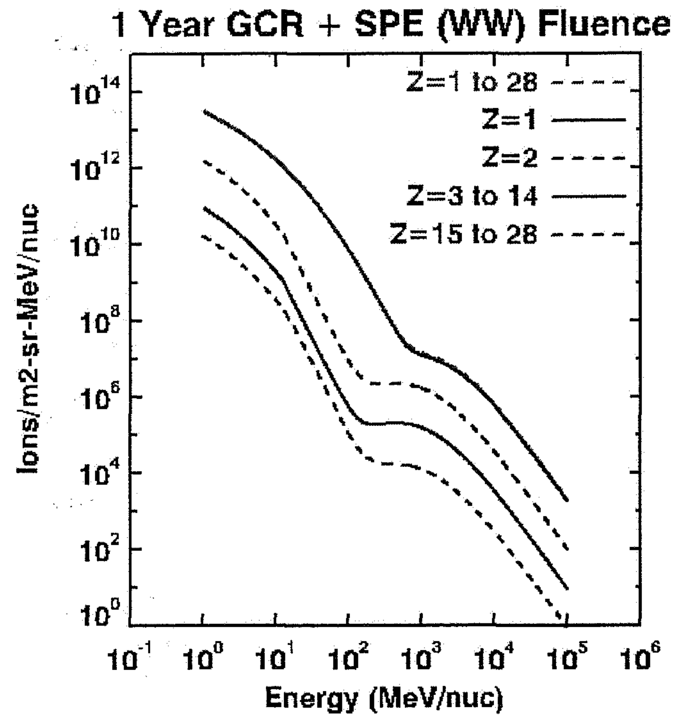




CREME 1996 [Tylka et al., 1997]

Galactic Cosmic Rays, Solar Energetic Particles



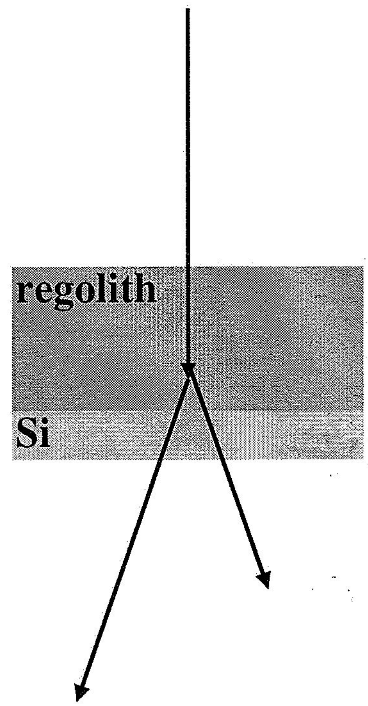


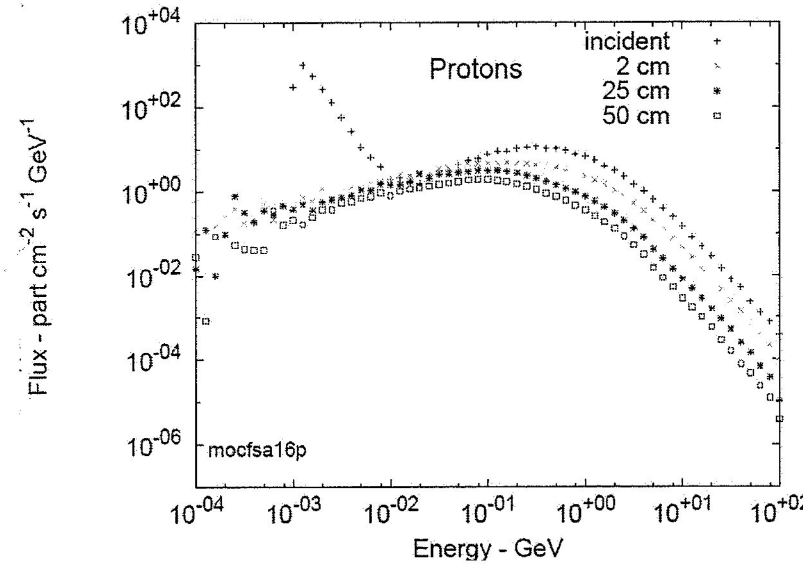
- **CREME96 Worst Week + 1 year GCR** (solar min)
- **Flare environment dominates at energies less than few hundred MeV**
  - **Particles responsible for total dose issues removed by shielding**
  - **Energetic (100's MeV to multiple GeV) particles difficult to shield**
    - Electronics upsets
    - Crew dose

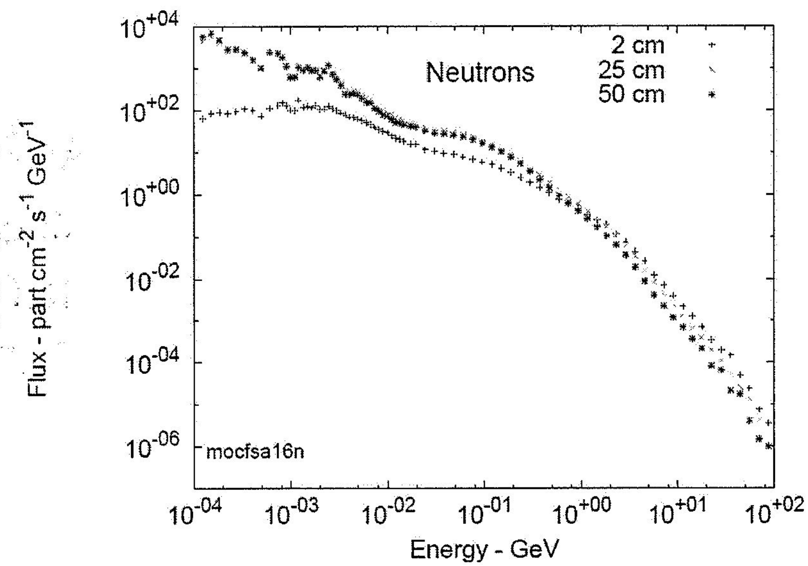
Regolith Shielding Properties for GCR

- **FLUKA transport code**
- **Shield with Apollo-16 lunar soil composition**
- **CREME96 GCR Z=1 solar minimum**
  - **Isotropic incident flux over hemisphere**

Compound	Percent A-16	Percent JSC-1
Na_2O	0.46	2.70
Al_2O_3	27.30	15.02
FeO	5.10	7.35
CaO	15.70	10.42
Fe_2O_3	0.07	3.44
MnO	0.30	0.18
MgO	5.70	9.01
SiO_2	45.00	47.71
K_2O	0.17	0.82
TiO_2	0.54	1.59
P_2O_5	0.11	0.66
Cr_2O_3	0.33	0.04

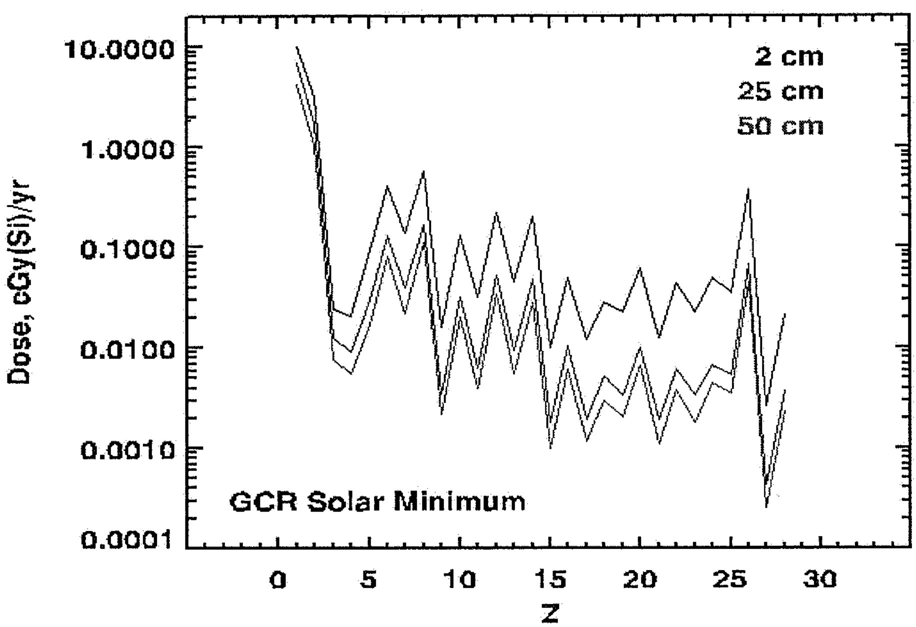






GCR Dose

Shielding (Apollo-16 soil)	GCR Dose (FLUKA) ($1 \leq Z \leq 28$)
2 cm	15.9 cGy/yr
25 cm	9.3 cGy/yr
50 cm	5.6 cGy/yr



Deterministic LEO Dose Limits*

Dose Equiv. (cSv)

	BFO	Ocular Lens	Skin
30-day	25	100	150
Annual	50	200	300
Career	100-400	400	600

* [NCRP-98-1989] (from Wilson et al., 1997)

Misson Dose (cSv) Estimates
(50 cm regolith shielded cylinder)

	GCR	Feb 56 Flare	Mission Dose
30-days	1	7.5	8.5
6 months	6	7.5	13.5
1 year	12	7.5	19.5

(from Simonson et al., 1997)

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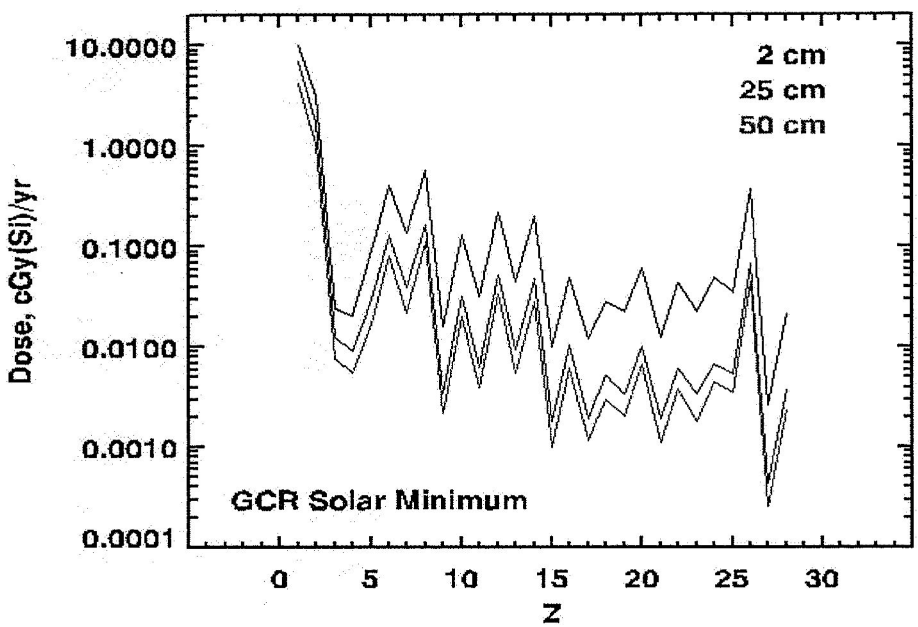

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(from Simonson et al., 1997)

Evaluating stochastic human dose risk requires more detailed analysis!

Total Ionizing Dose Comparison

- ESP solar proton model [Xapsos et al., 2000]
- AE-8/AP-8 trapped radiation environments

- Mission:

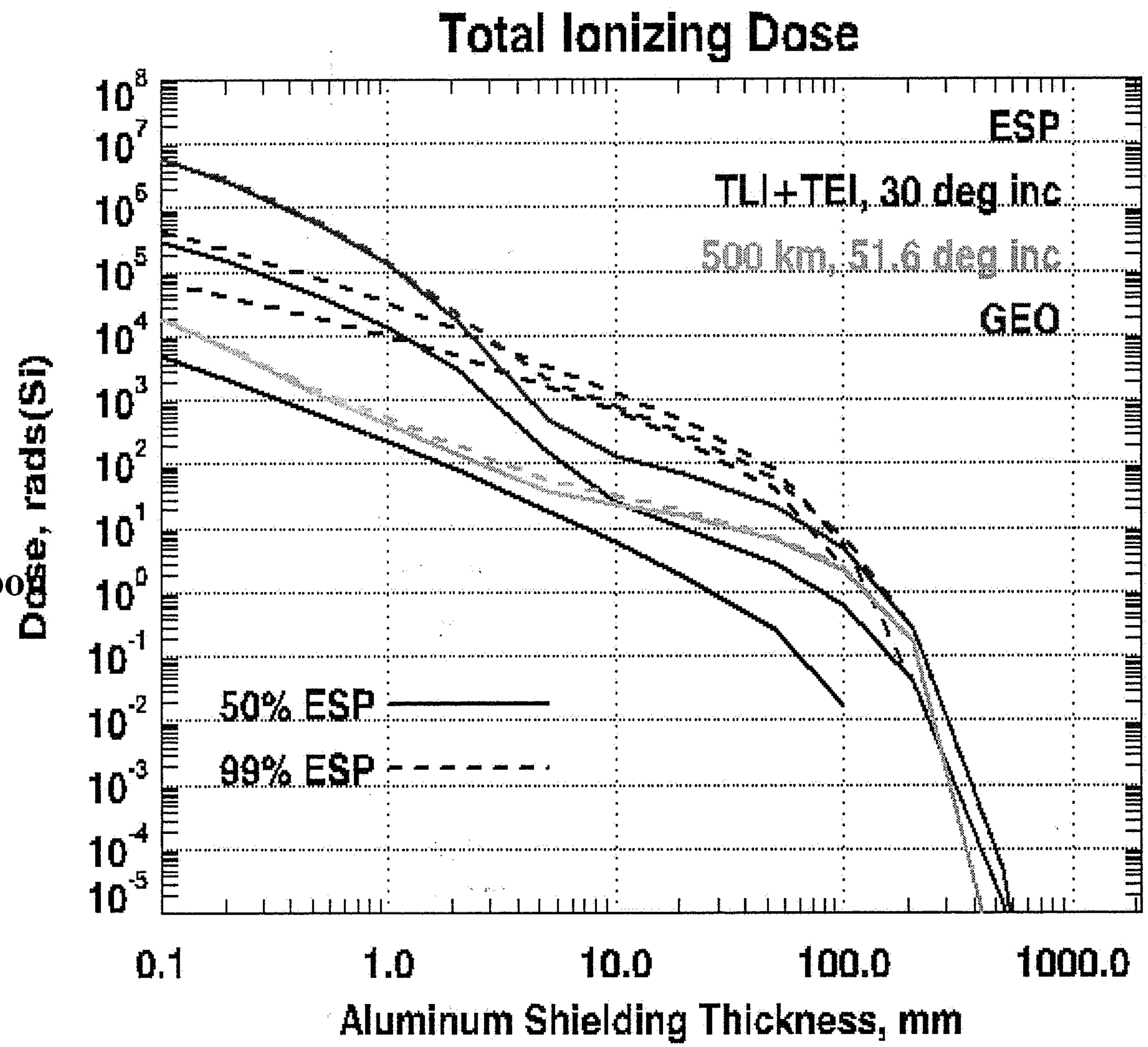
1 TLI trajectory to Moon

1 TEI trajectory from Moon

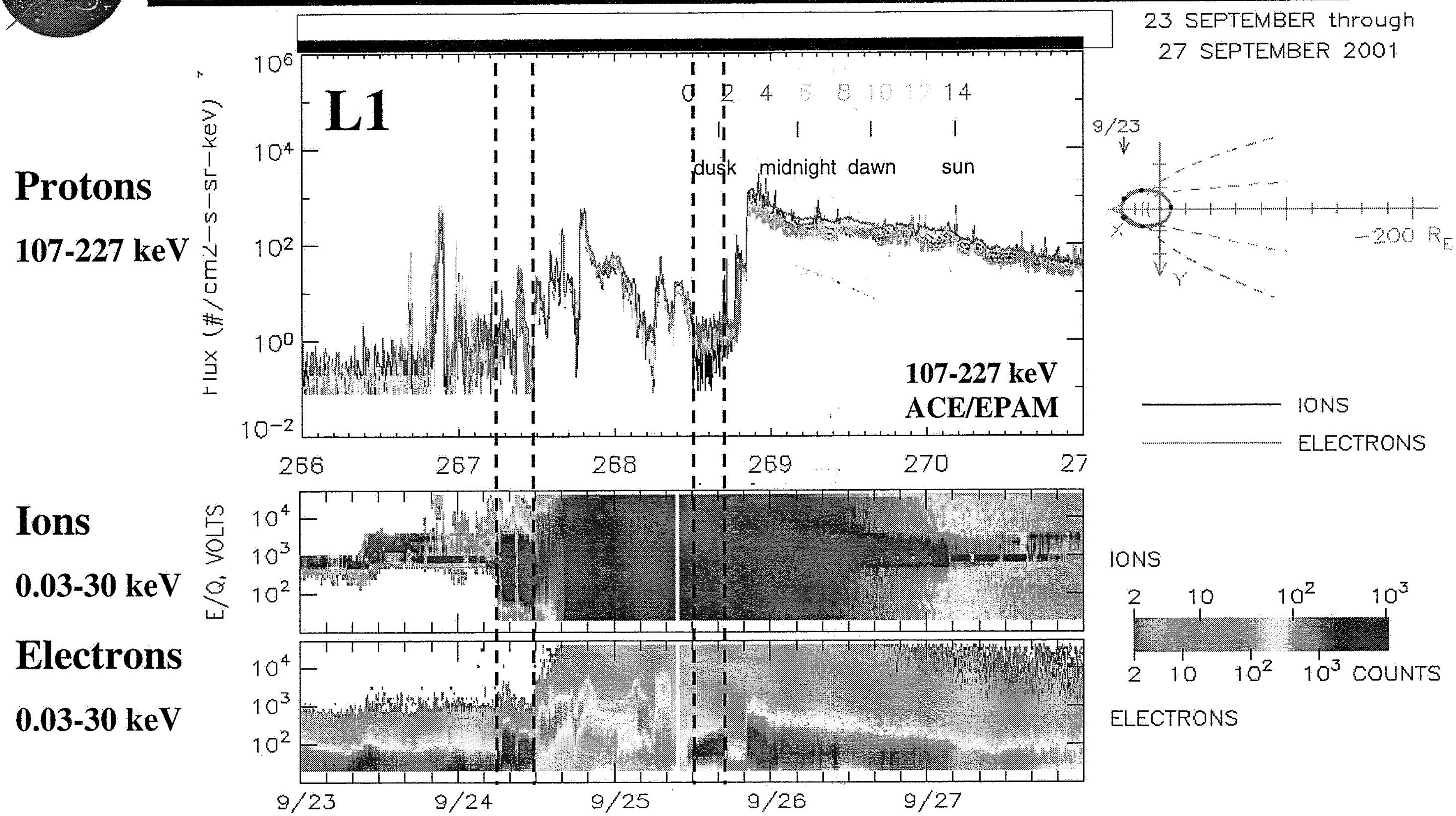
Single flare during 1 year on Moon

Neglect GCR

- ISS 1 year
- GEO 1 year



Energetic Particle Access to Magnetotail

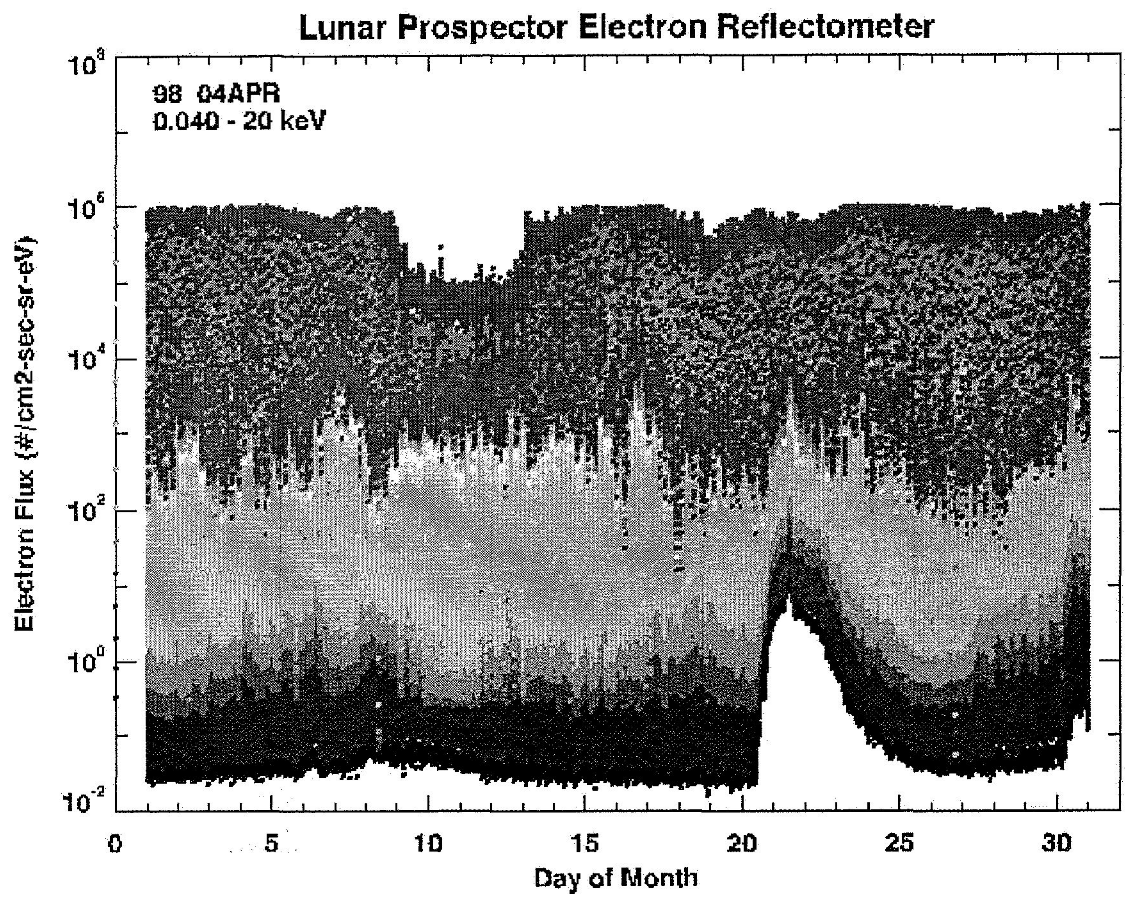


Solar energetic particles have nearly free access to outer magnetosphere and magnetotail—no protection for Moon when in magnetotail

Lunar Radiation Environments

- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV

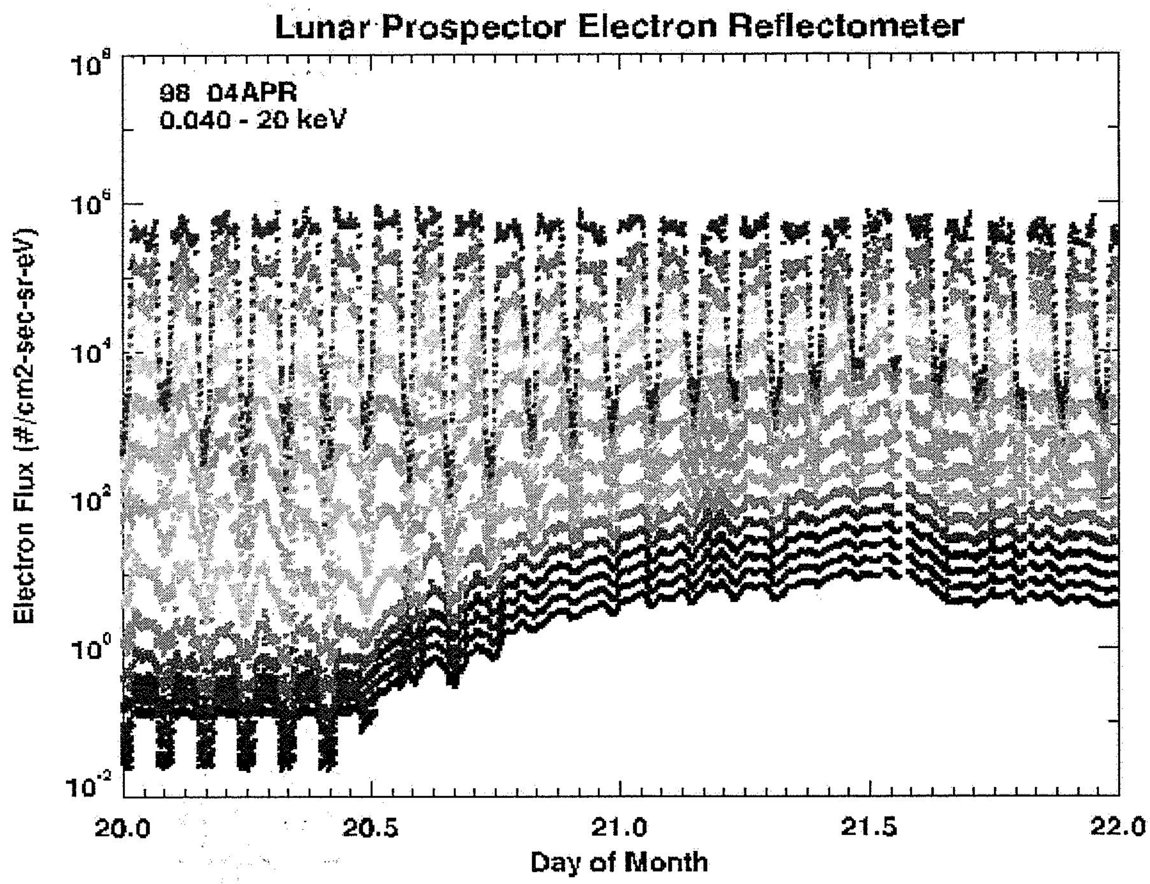
- April 1998
  - Earth's magnetotail
  - Solar energetic particle event



Lunar Radiation Environments

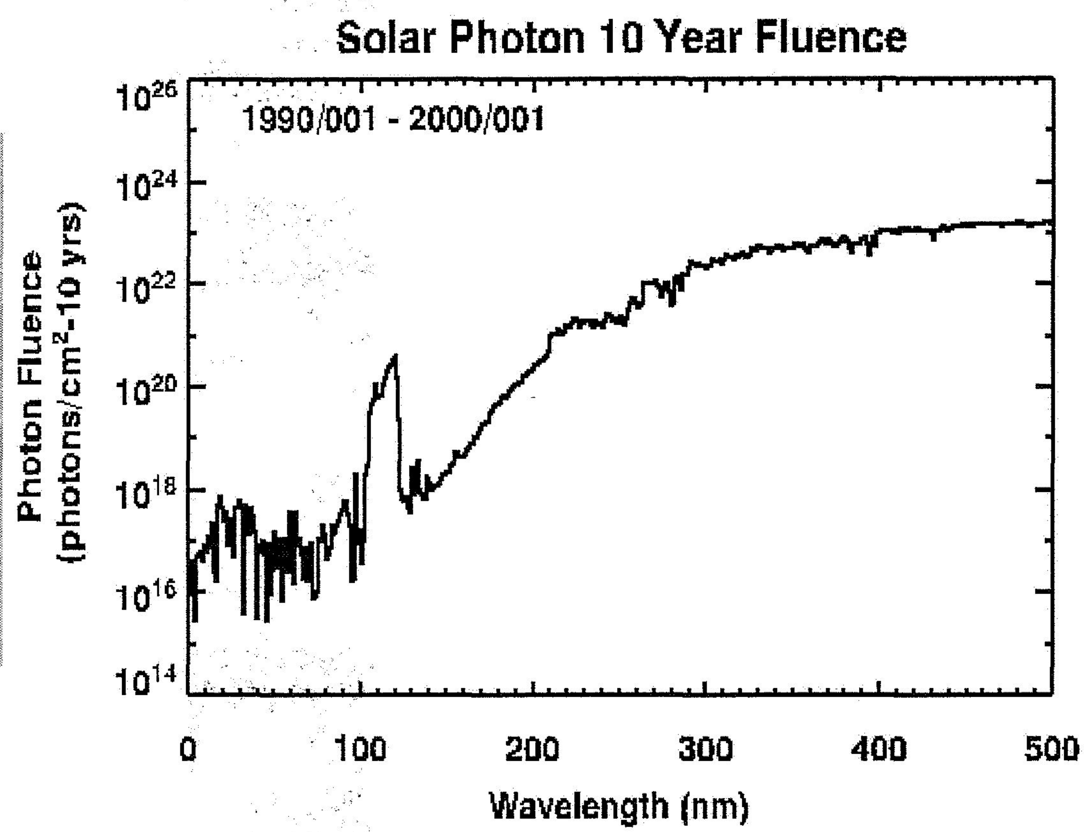
- **Lunar Prospector Electron Reflectometer**
  - **Spin average electron flux**
  - **~40 eV to ~20 keV**

- **4-5April 1998**
  - **Moon in solar wind**
  - **Plasma wake**
  - **Solar particle event and wake**



Solar UV/EUV Photons

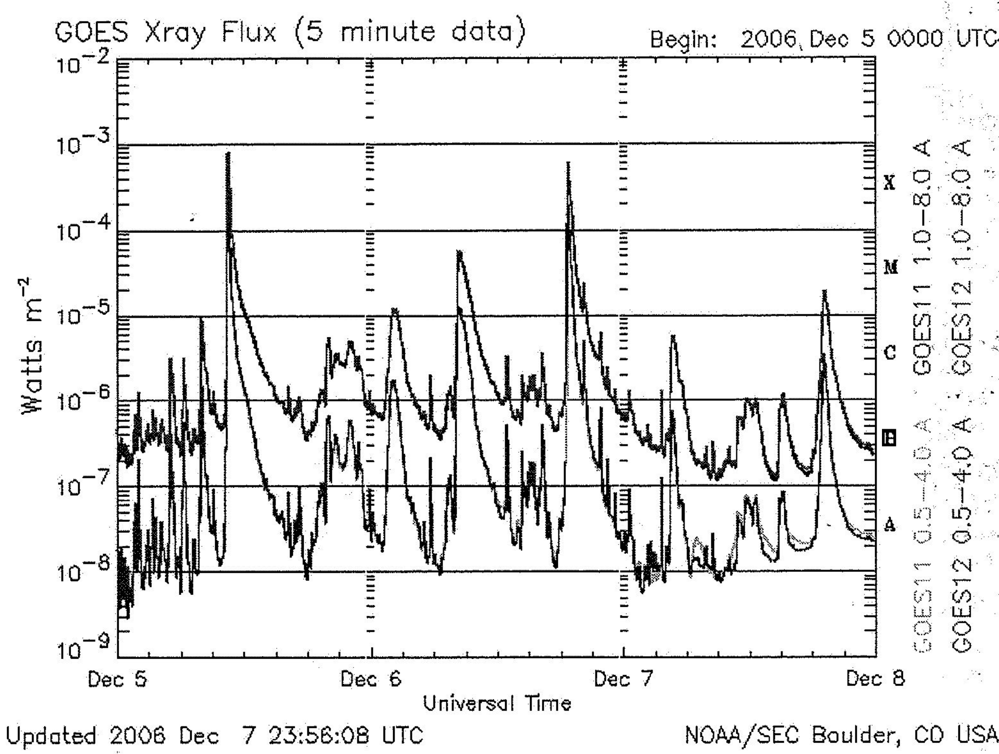
Lunar UV/EUV environment essentially same as LEO, GEO	Incident flux
--Transit	100%
Lunar:	
--Mid-latitudes	~50%
--Poles	0% to ~50%



- Proton fluence integrated from Solar2000 model [Tobiska et al., 2000]
- EUV (λ<120 nm) photon fluence for 10 years ~10^{17} photons/cm^2 nearly equal to solar wind fluence for 10 years (~$3x10^8$*$3x10^7$*10) = $9x10^{16}$16 ~$1x10^{17}$
- UV photon flux dominates solar wind at lower energies
  - Lyman-α (λ=121.6 nm) alone ~10^{20} photons/cm^2

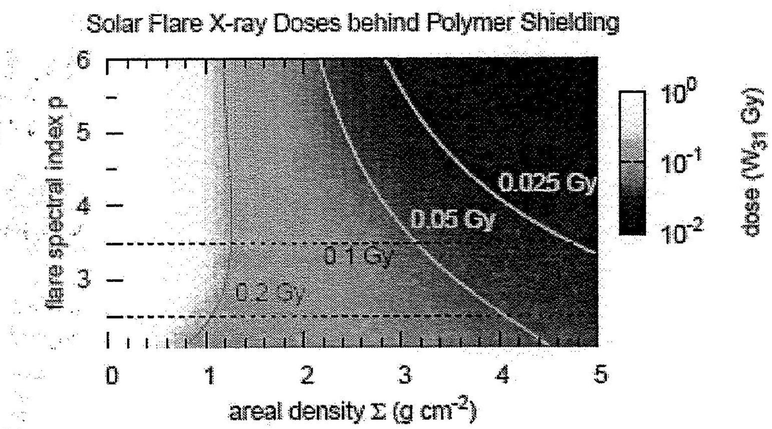
X-ray Photons

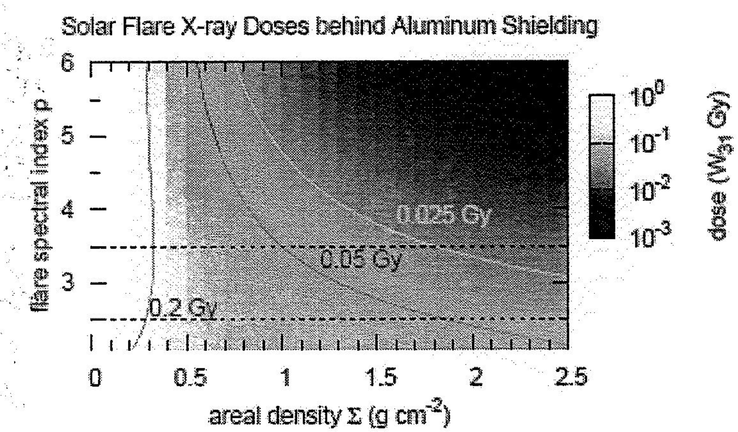
Large flares can generate sufficient photon fluence at x-ray energies to be a biological radiation concern in lightly shielded locations



Dose due to large flares [*Smith and Scalo*, 2007]

- **~10^{31} erg flare**
- **Flux ~ E^{-p} photons/cm^2-sec $2 < p < 6$**
- **10 keV – 511 keV**





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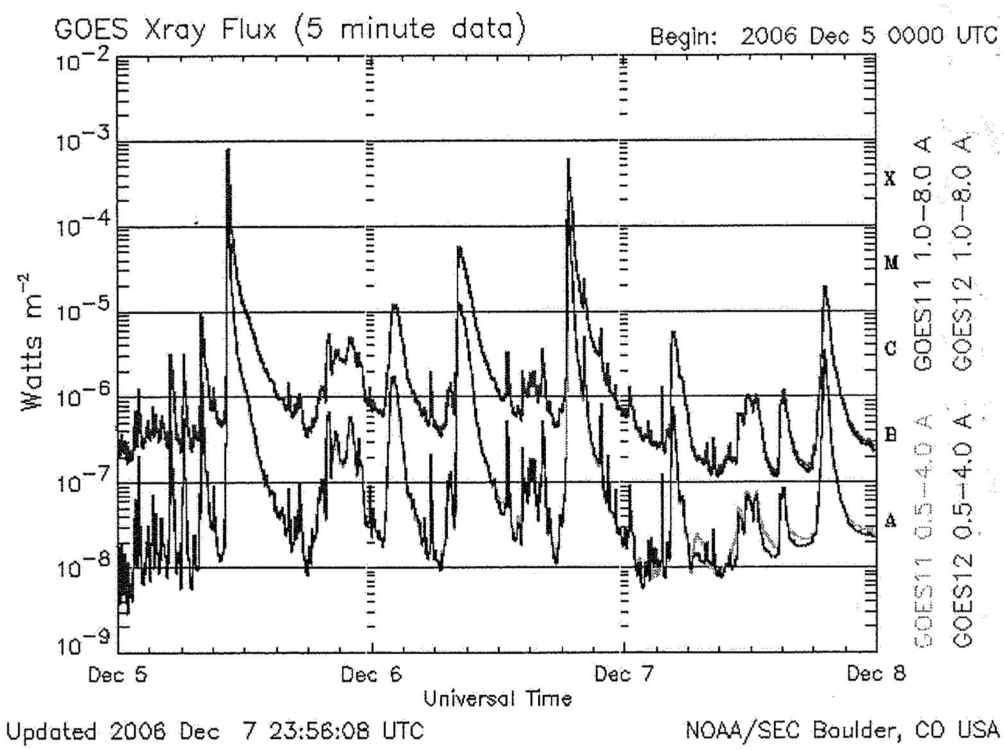

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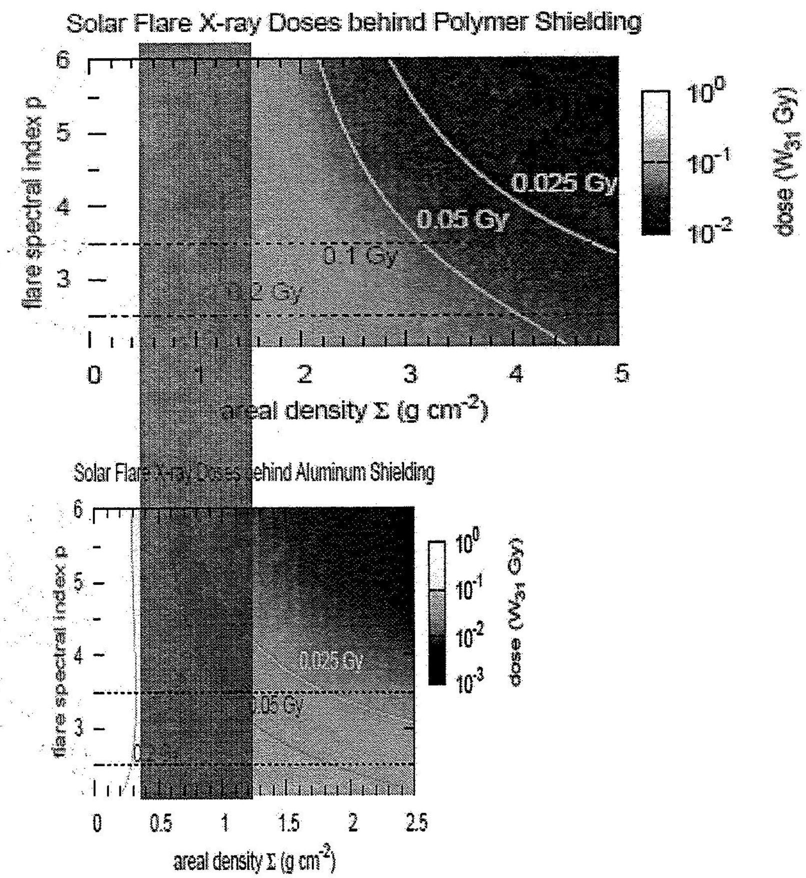


Large Flares

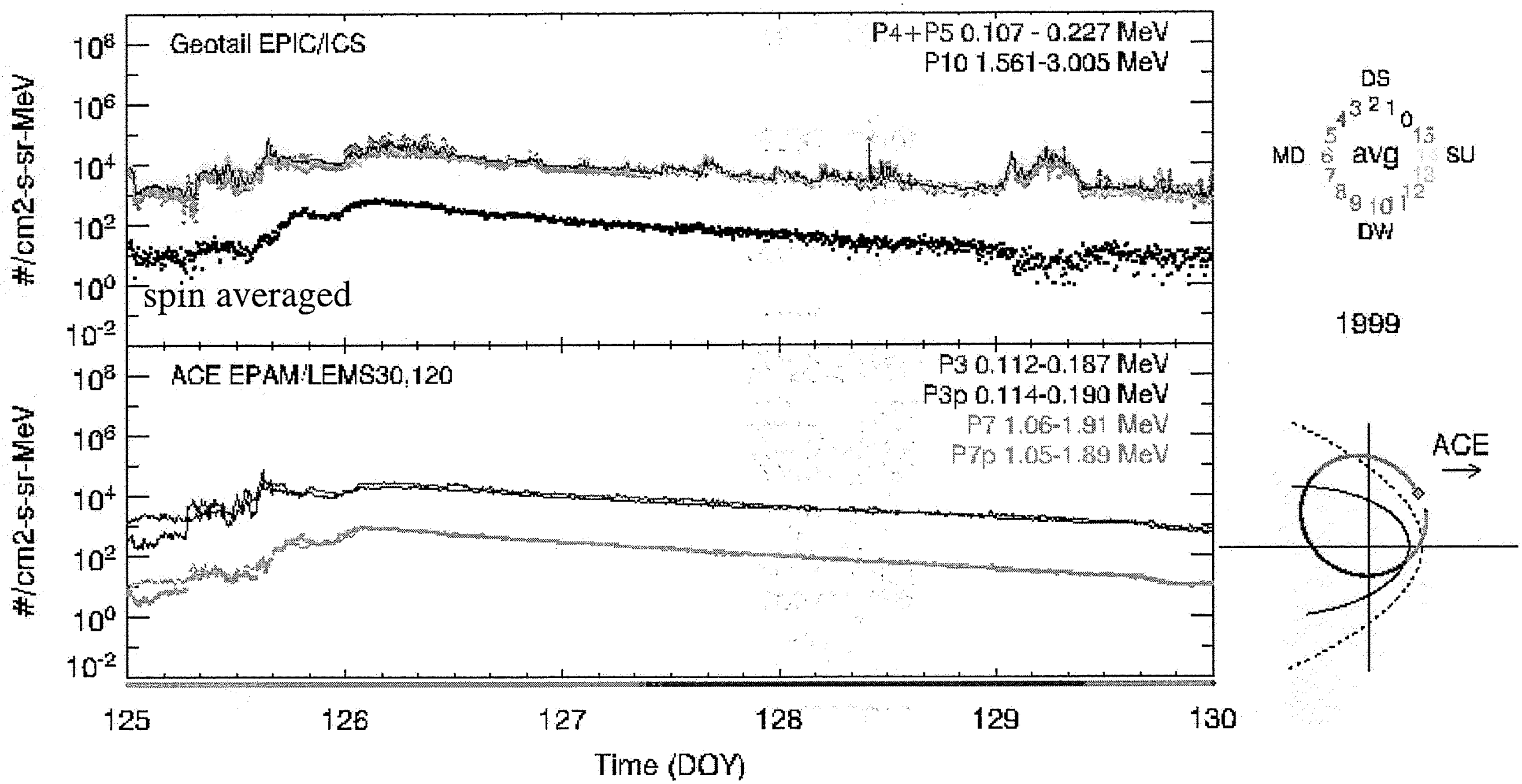
- Large X-class flares
  - Duration 5 - 30 min
- These same flare environments impact low Earth orbit EVA's
  - ISS construction
  - Shuttle EVA
  - Mir
  - Gemini, etc.
- LEO orbit periods typically ~90 min
  - 50% to ~100% of orbit exposed to flare depending on inclination and orientation of orbit plane
  - Experience derived from flare monitoring, dose evaluation in LEO EVA operations useful for developing lunar EVA concept of operations
- Challenge for lunar EVA
  - Limited warning, rise times ~minutes or less
  - Dose accumulates for 5-30 min periods instead of days required for energetic particle events
  - Large (10^{31} erg) x-ray flares are about 50x more common than 10^{10} p-cm^{-2} SPE's

Historic Large Flares

1	X28+	04/11/03		
2	X20.0	02/04/01	16/08/89	
3	X17.2	28/10/03	peak $4.6x10^{32}$ ergs	
4	X17	07/09/05		
5	X15.0	06/03/89	11/07/78	
6	X14.4	15/04/01		
7	X13.0	24/04/84	19/10/89	
8	X12.9	15/12/82		
9	X12.0	06/06/82	01/06/91	04/06/91
		06/06/91	11/06/91	15/06/91
10	X10.1	17/12/82	20/05/84	
11	X10.0	29/10/03	25/01/91	09/06/91
12	X9.8	09/07/82	29/09/89	
13	X9.4	22/03/91	06/11/97	
14	X9.3	24/05/90		
15	X9.0	05/12/06	06/11/80	02/11/92

(adapted from http://www.spaceweather.com/solarflares/topflares.html)

SPE Anisotropy



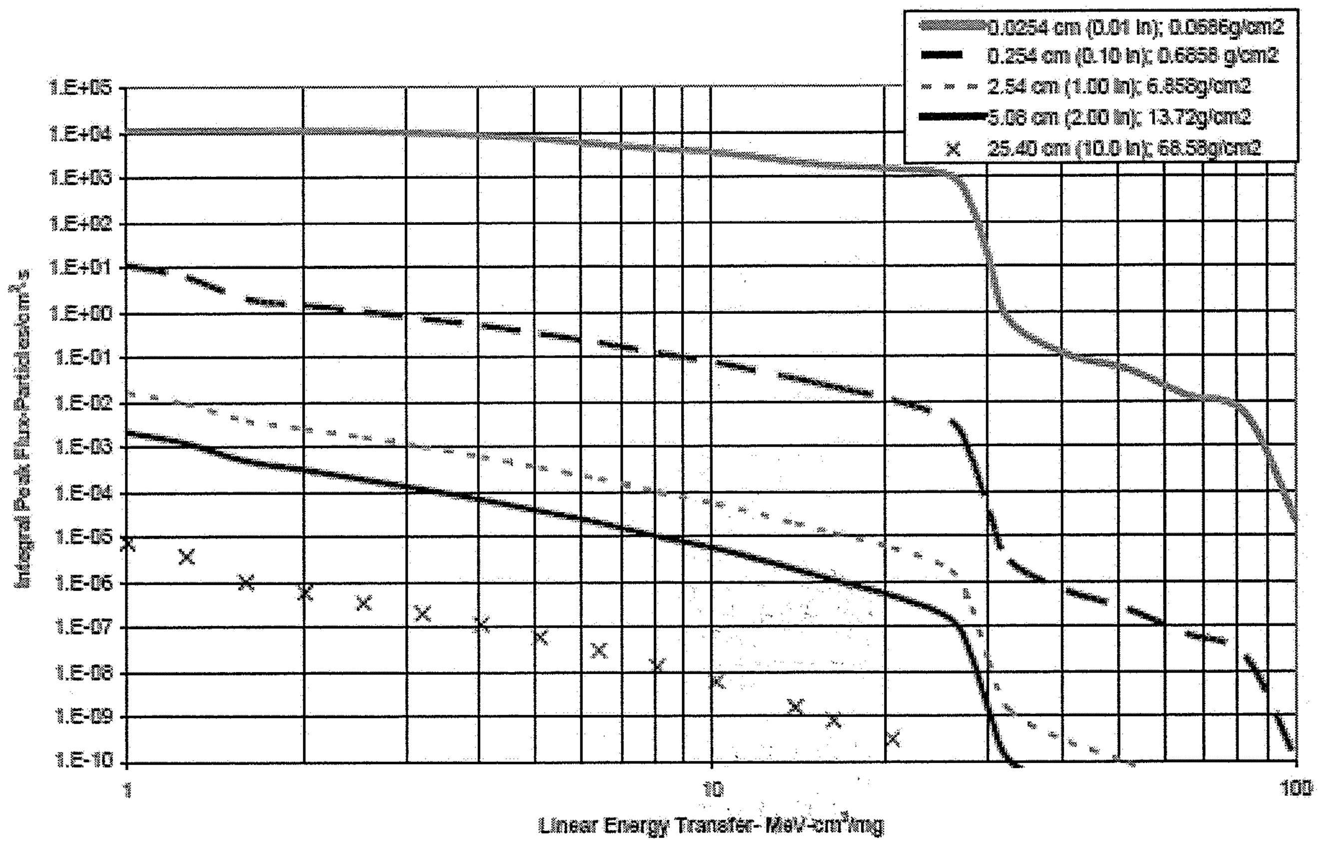
Constellation Design Environments

Design philosophy:

- Adopt credible extreme environments to assure hardware operations reliably with minimal interruptions due to space weather
- Let crew dose drive operations issues, hardware should not
- Design one system for operations in LEO, Earth-Moon transit, and lunar operations
  - Adopt most stressing radiation environment to drive design whether in LEO, GEO, or interplanetary space (solar energetic particles, GCR)

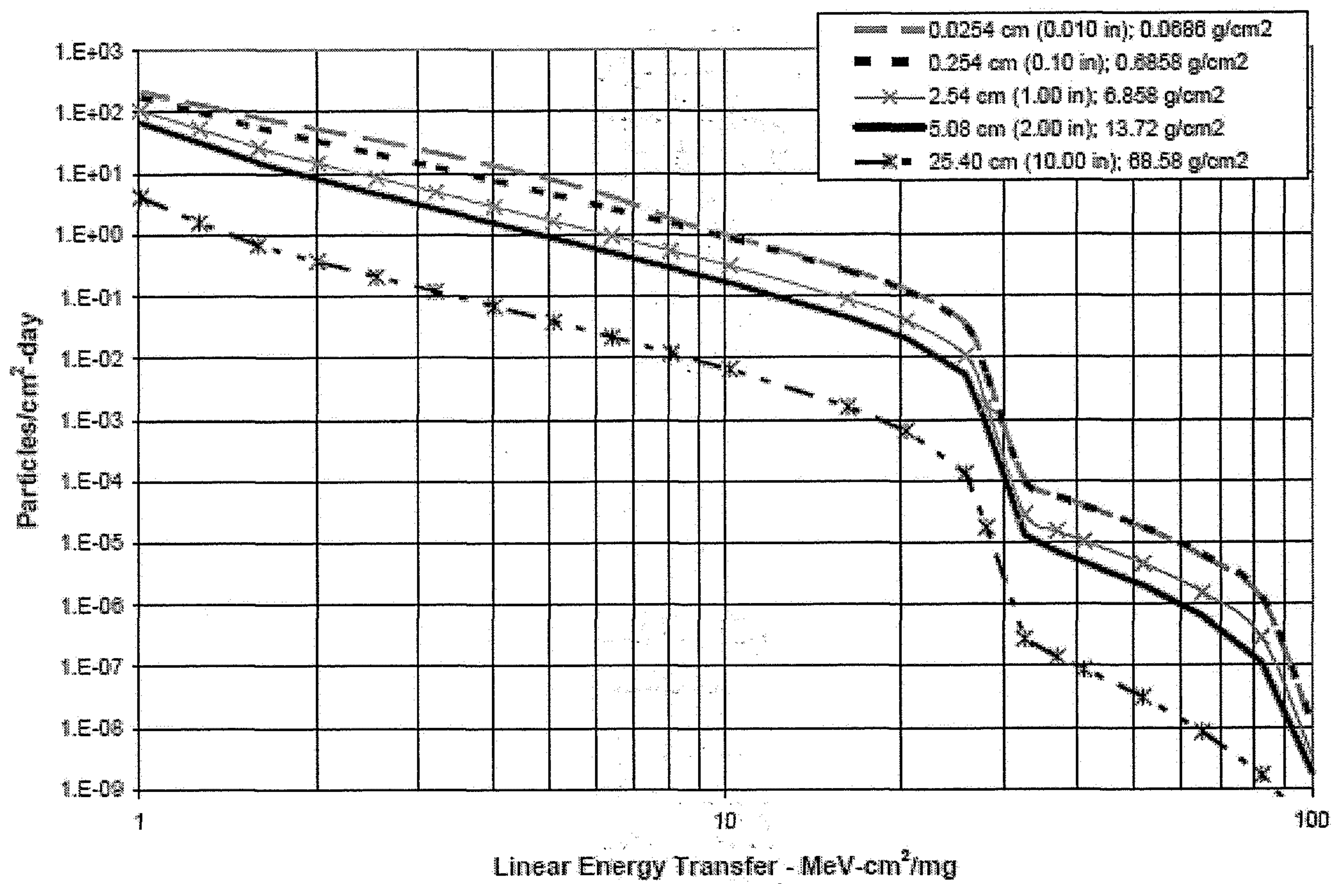
Constellation Design Environments

- Peak SPE LET flux spectra
  - Based on October 1989 flare environments derived from CREME96 model



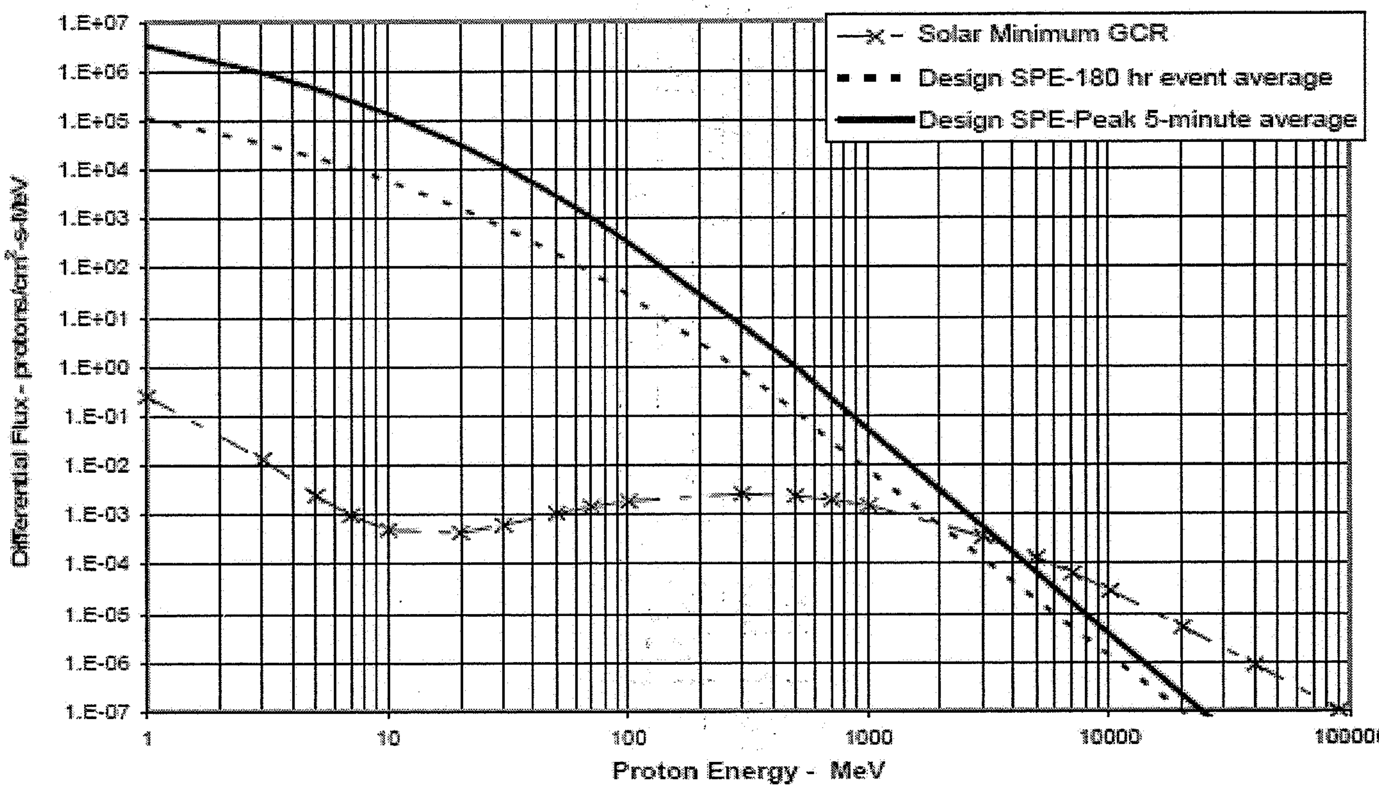
Constellation Design Environments

- GCR LET flux spectra
  - Based on solar minimum worst case GCR environments derived from CREME96 model



Constellation Design Environments

- Proton SPE, GCR flux spectra
  - Based on October 1989 flare environments derived from CREME96 model

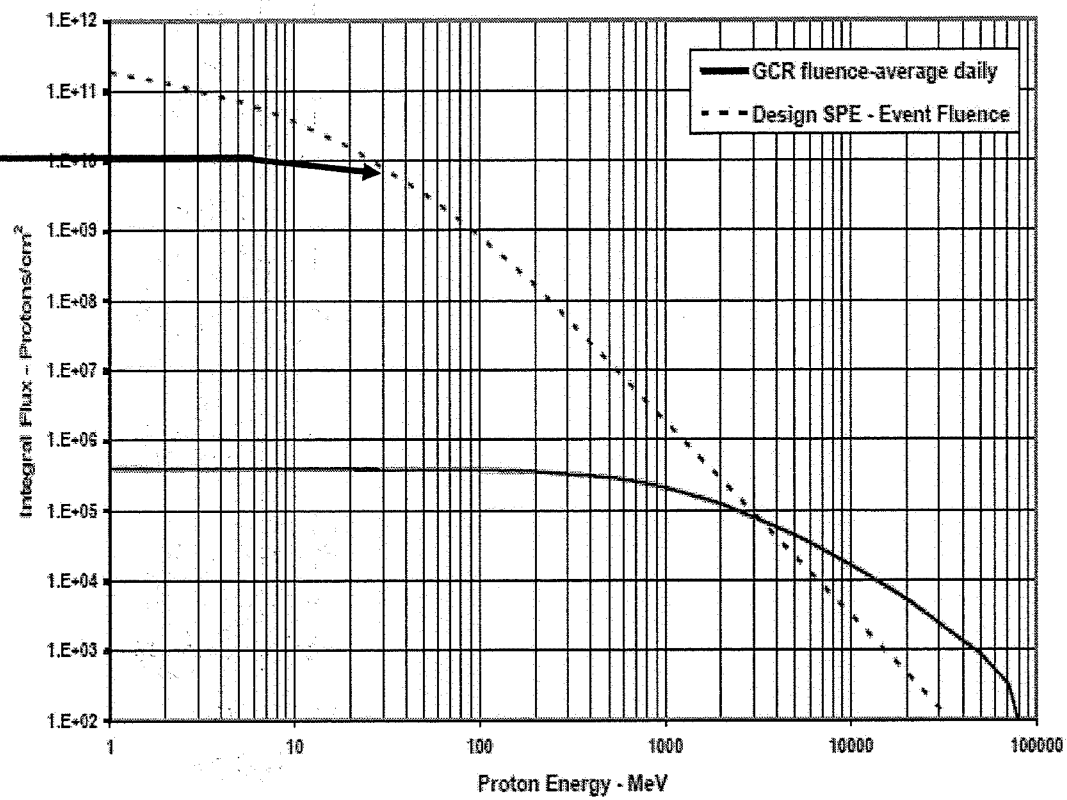


Constellation Design Environments

- Proton SPE, GCR fluence spectra (for total dose analyses)
  - Based on October 1989 flare, solar minimum GCR environments derived from CREME96 model

Event	Max >30 MeV flux (#/cm2-s-sr)	>30 MeV fluence (#/cm2)
1859/09/01	5×10^4	19×10^9
1960/11/15	-------	9×10^9
1946/07/25	-------	6×10^9
1972/08/04	2×10^4	5×10^9
2000/07/12	--------	4.3×10^9
1989/10/19	--------	4.2×10^9
2001/11/04	--------	3.4×10^9
2003/10/28	4.5×10^3	3.4×10^9
2000/08/00	--------	3.2×10^9
1959/07/14	-------	2.3×10^9
1991/03/22	--------	1.8×10^9
1989/08/12	--------	1.4×10^9
1989/09/29	--------	1.4×10^9
2001/09/24	--------	1.2×10^9
2005/01/15	---------	1.0×10^9

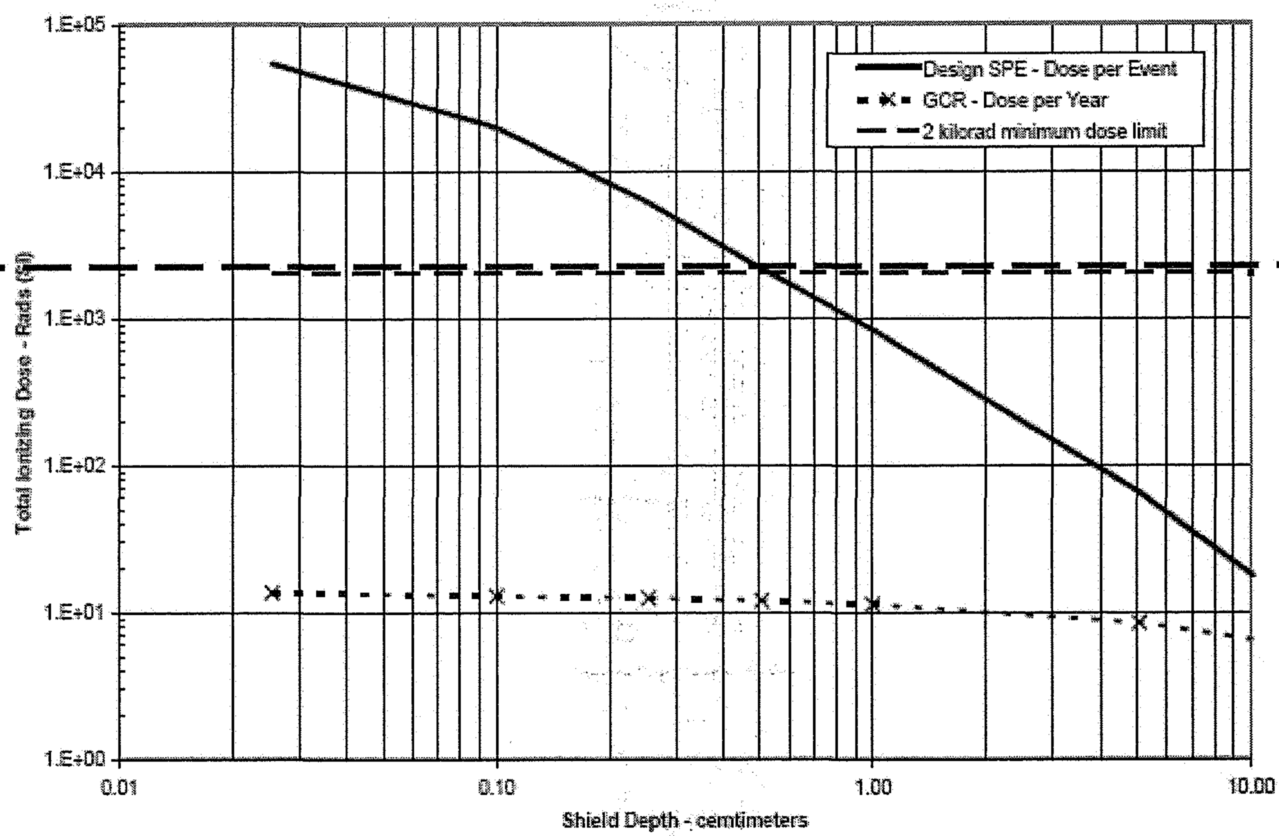
Sources: Smart and Shea, 2002; Reedy, 2006; Smart et al., 2005



Constellation Design Environments

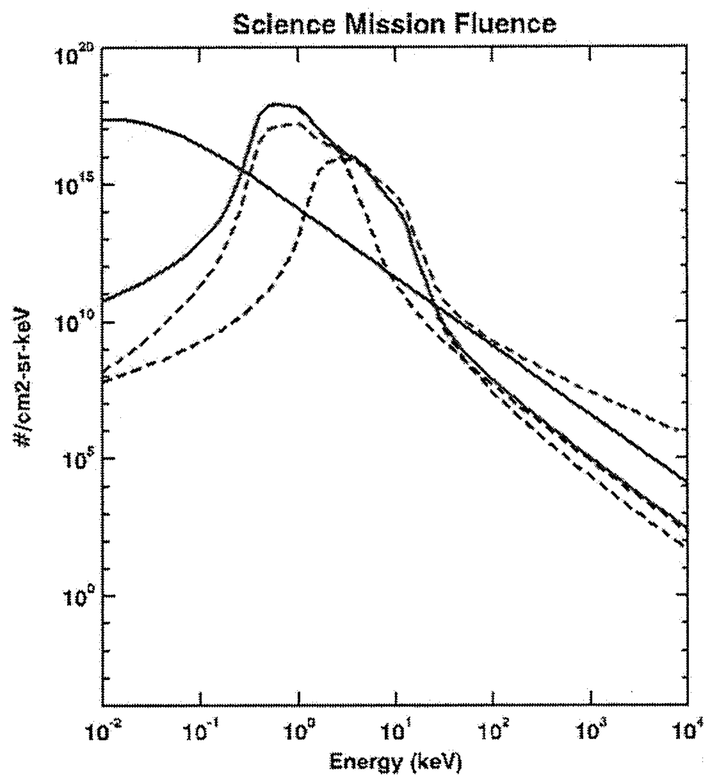
- Total ionizing dose
  - Based on October 1989 flare, solar minimum GCR environments derived from CREME96 model

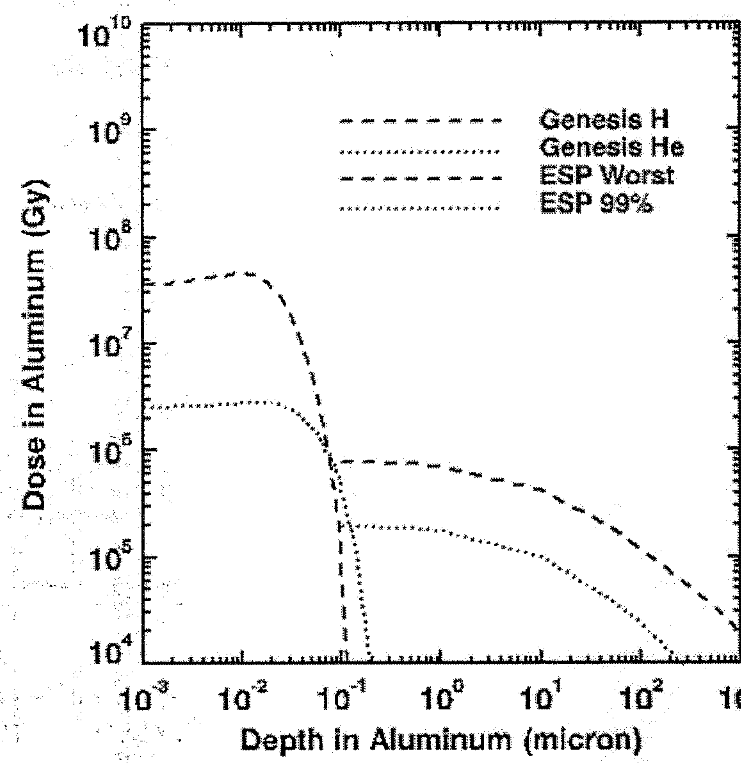
2 krad



Constellation Design Environments

- Solar wind environments
  - High flux, low energy environments relevant to optical properties of material surfaces
  - Genesis ~3 year solar wind ion fluence, dose estimates shown here





Summary

- **Radiation and plasma environments encountered during lunar missions similar to environments encountered in LEO, GEO missions**

- **Radiation environments are not significant threats for hardware and crew dose issues are not large for missions on order of year or less with adequate shielding:**
  - **Radiation belt transit**
  - **Solar energetic particles**
  - **Galactic cosmic rays**

- **Sufficiently conservative design environments are in place to assure reliable hardware operation with minimal impact from space radiation environments**